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THE USE OF TERRAIN HEIGHT INFORMATION FOR IMPROVING THE ACCURAC--ETC(U)
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by

P. A. Roberts

January 1982

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Technical Memorandum Space 297

Received for printing 12 January 1982

THE USE OF TERRAIN HEIGHT INFORMATION FOR IMPROVING THE ACCURACY OF CLASSIFICATION OF LANDSAT DATA

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SUMMARY

One potentially important area of work in remote sensing is the use of topographic data in conjunction with satellite imagery to improve the accuracy of classification algorithms. This Memorandum is concerned with techniques for using terrain height data in conjunction with Landsat imagery. An algorithm is described that transforms digitised height contours into an equispaced grid of points. A method is also described which utilises this height matrix to derive the magnitude and direction of the slope of the terrain, information which can in turn be used to calculate the variation in direct solar illumination over an area. Finally, techniques are described for using terrain data to improve the accuracy of multispectral classification of Landsat data.

Extended version of a paper presented at the Annual Conference of the Remote Sensing Society, December 1981

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1 INTRODUCTION

Much more information can often be obtained from remotely sensed data if it is used in association with existing ground truth information. This paper is concerned with techniques for using topographic information from maps, in conjunction with imagery of land surfaces. An algorithm is described that can be used to transform digitised contour height information into an equispaced grid of points, a format that is suitable for easy manipulation and processing and for comparison with many types of digital imagery. The height matrix can in turn be used to derive the magnitude and direction of the slope of the terrain and the variation in the direct solar illumination arising from it. These quantities can all be displayed as grey tone images for independent interpretation or interpretation in conjunction with other imagery. In addition, the intensity of Landsat pixels can be adjusted so as to compensate for variations in direct solar illumination arising from undulating terrain.

In this Memorandum the factors that need to be taken into account when digitising a contour map are first briefly discussed. This is then followed by a description of a technique for producing a terrain height matrix from a contour height map. Subsequent sections deal with the parameters that can be obtained from the terrain height matrix and the display of these quantities as grey tone images. The final part of this Memorandum describes how terrain height data can be used to try to improve the accuracy of multispectral classification of Landsat data. In order to illustrate these techniques a small test area in Southern England has been selected.

2 DIGITISATION OF CONTOURS

Often the investigator will not have the contour information already digitised, but rather will only have a paper copy of the map thus necessitating digitisation of the contours. It is necessary therefore for the investigator to decide at what interval around contours points are to be digitised. The evaluation of this interval involves an estimate being made of the interval along a contour that can be represented by a straight line. This interval is dependent upon the grid spacing of the terrain height matrix and the curvature of the contour in question; the smaller the grid spacing or the greater the curvature of the contour, the smaller this interval must be in order to represent the contour to the required accuracy. More precisely, if d is the digitisation interval, r is the radius of curvature of the contour (which generally is a function of position along the contour) and s is the maximum permissible deviation of a straight line, joining two points on the contour, from the contour, then $d \approx \sqrt{8rs}$, where d is such that the angle the contour turns through is small. The author has found that for his work it is adequate that s be half the grid spacing, but this may not be acceptable for all applications.

If the digitisation interval is greater than d then the contour is under-digitised, and if it is less it is over-digitised. The only consequence of the latter is that the number of data points describing the contour is greater than necessary.

Contour fitting algorithms that are considerably better than linear interpolation can be employed and should be adopted when contours are under-digitised. A description of one such algorithm can be found in Ref 1.

The digitisation of contours can take either of the following forms (amongst others):

(i) Constant separation between data points.

(ii) Variable density system with the interval between data points depending upon the curvature of the contour. This reduces the number of points required to describe a contour.

If it is decided to opt for a constant separation between data points then the map will be correctly digitised if the evaluation of the digitisation interval is based upon the smallest radius of curvature. The variable density method requires a continual evaluation of the curvature of the contour being digitised and is best suited to automated digitisation. If the digitisation is being performed manually using this method then the investigator must make a subjective estimate of the required digitisation interval.

3 TRANSFORMING DIGITISED CONTOURS INTO A HEIGHT MATRIX

The basic problem in generating a height matrix is to fit a surface to the contour data such that every contour lies on the surface. Since it is assumed that there will be no further information available as to the nature of the surface, the intuitively desirable conditions of smoothness and continuity are adopted. This surface can then be sampled at the appropriate points to produce the required grid. It should be remembered that the surface has to be constrained such that between contours it remains within the range of values defined by the contours.

The method adopted does not perform a true two-dimensional fit but instead takes the average of two orthogonal one dimensional fits. This involves two orthogonal sets of cuts being taken across the contour map; the points of intersection between these grid lines define the points at which interpolated data is required. For each grid line the points of intersection of the line with the contours are calculated and then interpolation is carried out along the grid line to obtain values at the grid points lying on the line. Also produced are weighting values reflecting the confidence in the interpolated values. This procedure results in two grids of points being obtained corresponding to the two sets of cuts, together with two grids containing the associated weighting values. These weighting values are used to combine the grids to produce the final height matrix.

It is necessary to take two mutually orthogonal sets of cuts across the map since it may be that some contours run parallel to one of the sets of cuts and thus would be ignored by that set unless they fell exactly on the cuts. Contours missed by one set of cuts are therefore incorporated in the orthogonal set. In this way the orientation of the cuts with respect to the contour map is not important, whilst it may be crucial if only one set of cuts were to be taken.

When converting a contour map into a height matrix it is necessary to define a grid spacing. It should be remembered that the smaller the grid spacing the more accurately the contours can be reconstructed from the height matrix, and in any case it should be no greater than half the scale size of the smallest feature it is required to preserve in the transformation. Fig 1 shows a 5 km square area of Hampshire after digitisation of the contours and spot heights from a 1:25000 Ordnance Survey Map (sheet SU54). This map has been converted into a grid 500 × 500 using a 10 m grid spacing. The accuracy of the height matrix can be ascertained by comparison with the spot heights for the area, although it should be realised that beyond the outermost contours the interpolation technique is not very reliable. Values can be derived from the height matrix at the positions of the spot heights by using the 16 surrounding matrix values. A comparison between the two sets of values is given in Table 1. As is to be expected, there are no differences greater than the contour interval of 25 ft. The mean difference between the two sets of heights is only 0.04, a value that is probably rather fortuitous for a sample of only 21 points. The standard deviation of the differences is 7.1 ft.

A much more detailed description of the algorithm used to generate the height matrix from contours is given in Ref 1. This reference also includes a description and a listing of a computer program that can be used for evaluation of the algorithm. Further information and refinements of the algorithm are to be found in Ref 2.

4 QUANTITIES DERIVED FROM THE HEIGHT MATRIX

Using the height matrix it is possible to derive the magnitude and direction of the gradient of the terrain. Henceforth in this Memorandum the magnitude of the gradient will be referred to as slope and the direction as aspect. The slope and aspect are derived from the x and y direction gradients m_x and m_y that are obtained from a least squares fit of a two dimensional second order polynomial over a small $n \times n$ matrix of points. This least squares fitting is considerably simplified by the fact that the points are an equispaced grid and the point of interest is the one at the centre. The least squares fit is performed using either 3 × 3, 5 × 5 or 7 × 7 points depending upon how much smoothing is considered desirable.

The slope and aspect are obtained from the x and y direction gradients m_x and m_y as follows:

$$\text{slope} = \tan^{-1}\left(\sqrt{m_x^2 \times m_y^2}\right)$$

$$\text{aspect} = \tan^{-1}\left(\frac{m_x}{m_y}\right) \qquad \text{if slope} \neq 0$$

$$= \text{undefined} \qquad \text{if slope} = 0.$$

The direct illumination from the Sun at a point on the ground can in turn be obtained from the slope and aspect, viz:

$$I_s = \{\cos(\alpha - \gamma) \cos \beta \sin \delta + \sin \beta \cos \delta\} I_0$$

where α is the Sun azimuth, β is the Sun elevation, γ the aspect, δ the slope and I_0 the solar illumination on a unit area perpendicular to the direction of the illumination; α and γ are measured from north. It must be emphasised that this equation only refers to direct illumination and neglects totally the not insignificant contribution that will arise from backscattered radiation. A quantity that is particularly useful in investigating the variation in brightness arising from the surface topography is given by:

$$R_d = \frac{\sin \delta \cos(\alpha - \gamma)}{\tan \beta} + \cos \delta \ .$$

This quantity, which henceforth will be referred to as the variation in direct solar illumination, is unity for flat terrain, greater than unity for terrain inclined towards the Sun, less than unity for terrain inclined away from the Sun and negative for terrain in shadow. Also, the variation in R_d over a given area increases as the Sun elevation decreases.

Neither of these equations takes into account the possibility that some parts of the terrain may be shaded from direct illumination by others. Thus, these equations are only valid for all values of the terrain aspect and Sun azimuth angles when the Sun elevation angle is greater than the steepest slope, *ie* $\beta > \delta$.

5 DISPLAYING TERRAIN PARAMETERS AS GREY TONE IMAGES

Height, slope and variation in direct solar illumination present no problems in being displayed as grey tone images, since lower values can be assigned to lower pixel intensities and higher values to higher pixel intensities. Aspect can also be displayed as a grey tone image although the interpretation of such an image is rather more difficult. This is because:

(1) The aspect can vary between 0° and 360°, however 0° and 360° represent the same direction.

(2) The aspect for flat terrain is undefined.

(3) The value of the aspect becomes more unreliable as the slope becomes smaller.

One convention that can be adopted for displaying aspect and the one that is adopted here, although there is some ambiguity in the interpretation of the minimum and maximum permissible image intensities, is to assign an aspect value of 0° to an intensity of zero, 360° to the maximum image intensity, and flat terrain to a zero image intensity. Other conventions can of course be envisaged.

When considering the height matrix as a grey tone image it must be remembered that each value is associated with the centre of a pixel and does not represent the average value over a pixel. Where the terrain is changing slowly compared with the size of a pixel then the values of the height matrix will be a good approximation to the average value over a pixel. However, where the terrain is changing rapidly compared with the

pixel size the height estimate will not necessarily be a good approximation to the mean value over a pixel. In this situation the height matrix must first be evaluated using a grid spacing for which the terrain is changing slowly and then a suitable average taken to obtain an estimate of the mean value for the required pixel size. This technique can also be applied to the variation in direct solar illumination but it cannot be applied to the slope and aspect. For these quantities it is necessary to evaluate the mean x and y direction gradients in the manner described and thence to derive the mean slope and aspect.

As an example, the central 4 km square area of the map shown in Fig 1 has been converted to a height matrix using a grid spacing of 10 m. This was then used to derive the height, slope, aspect and variation in direct solar illumination corresponding to 50 m pixels. (The reason for choosing this pixel size will become evident in the next section.) The values associated with the pixels have been obtained by using the 25 values of the matrix covering each pixel. The four terrain parameters are displayed as grey tone images in Fig 2.

6 APPLICATION TO LANDSAT IMAGERY

6.1 Methods of employing terrain data

Recently, an increasing amount of interest has been given to the possibility of improving the accuracy of multispectral classification with Landsat imagery by taking into account effects arising from surface topography. These effects arise from the fact that although two areas may have the same cover type, and thus for a given spectral band would be expected to have the same intensity, in practice they will have different intensities if the terrain is such that the two areas receive differing amounts of illumination. If data describing the surface topography is available it should be possible to reduce this topographic effect and thus improve the accuracy of classifications. This can be achieved by two methods: one method involves using the terrain parameters as extra image planes and the other involves modifying the pixel intensities in the Landsat image.

In the first method, the four terrain parameters can be considered as four additional image planes to be used in conjunction with the four image planes associated with the four spectral bands of a Landsat scene. All eight image planes can be analysed together either on an interactive image processing system such as the IDP3000 [3] or on a computer. Thus, in classification, it would be possible to consider only areas exceeding a specified height or only flat areas. When classifying areas of similar cover type the reliability of the classification may be improved by performing a series of classifications each involving pixels which represent areas which received similar amounts of illumination. This can be achieved by using the image plane containing the variation in direct solar illumination in conjunction with the four Landsat image planes.

The second method of improving the reliability of classification is rather more difficult and involves more assumptions. Here, corrections are made to the intensity of pixels so as to account for both the variation in illumination and for the scattering properties of the surface. The total illumination consists of direct solar illumination

and a contribution from a diffuse component comprised primarily of scattered skylight, although there is a small contribution from light scattered onto the surface by surrounding ground. The diffuse component has been shown to be a small proportion of the total illumination, *ie* less than 12% of the total for each of the four Landsat bands for a Sun elevation of 34° under clear sky non-hazy conditions (Ref 4), conditions which will be satisfied by many Landsat scenes that would generally be considered suitable for classifying surface features. A further complication arises from the fact that most natural surfaces have preferred directions of scattering and this should be taken into account. This is difficult because the scattering properties of surfaces are dependent upon their composition and roughness and hence are hard to model. Further, the nature of the scattering may be heavily dependent on transient conditions, *eg* the presence of surface water on vegetation after rain or a heavy dew. Because of the complexity of the problem the far from insigificant effect due to the scattering properties of the surface are ignored here. A detailed discussion of the nature of scattering by natural surfaces can be found in Ref 5. Thus, assuming that all surfaces scatter light equally in all directions, pixel values can be adjusted so as to take account of variations in the surface illumination by using the formula:

$$I_c = \left(\frac{1 + r}{R + r}\right) I_u \qquad \begin{cases} R = R_d, & R_d \geqslant 0 \\ R = 0, & R_d < 0 \end{cases}$$

where I_u = uncorrected pixel intensity

I_c = corrected pixel intensity

and r = diffuse component expressed as a fraction of the direct illumination on a horizontal surface

It must be realised that attempting to correct pixels in shadow will not be expected to produce much improvement in classification because of the small range of pixel values in such areas.

To illustrate the effects of this technique, a Landsat scene covering the area illustrated in Fig 1 has been selected. Each of the four Landsat bands has been destriped, geometrically corrected and brought into registration with the National Grid. A subscene corresponding to the central 4 km square of Fig 1 has been extracted from the main scene to enable direct comparison to be made with the terrain parameters for the area. The pixel size for the Landsat data has been selected to be 50 m square so as to preserve as much as possible the accuracy of the original data. (The Landsat image has to be resampled during the geometrical correction process. For further details see for example Ref 6.) A late Autumn scene (25 November 1978) with a Sun elevation of only 15° has been selected so as to highlight the effect of the variation in direct solar illumination over undulating terrain. In comparison, all but 10% of the pixels are associated with slopes less than 5° and the mean slope is only 2.7°. Each Landsat pixel was modified using the above equation with a value of 0.14 being adopted for r. Fig 3 shows the Landsat band 7 image, corresponding to the central 4 km square of Fig 1, both before and after correction. Fig 3a is the original data after a suitable contrast stretch has been performed and Fig 3b is the same image but after the topographic correction

has been applied. As can be seen from a comparison of the two images, the correction has quite a marked effect, which is perhaps especially important since the test area is typical of many areas of gently undulating terrain found in Southern England. The effect will be expected to be even greater in areas where steeper gradients exist and farther north where lower Sun elevations are encountered.

In the above analysis the Sun elevation angle has been assumed to be the same over all the test area. This is a reasonable assumption here since the test area is only 4 km × 4 km, but allowance should be made for the variation in Sun elevation angle if large areas are considered. For example, over a Landsat scene of the UK the variation is of the order of 2^o, which can give rise to significant effects for low Sun angles.

6.2 Comparison of different classification techniques

The extent of any improvement in the accuracy of classification using Landsat data when combined with terrain data can only be ascertained by comparison with classifications which do not involve the use of terrain data, and by comparison of these classifications with ground truth data. Before describing the results of different classifications it is important to understand the classification procedure that is employed. First, an area is selected (often referred to as the 'training' area) over which it is known that the cover type of interest lies and it is assumed that all pixels within this area are part of the class of interest. The minimum and maximum intensities for each band are then determined for these pixels and then all other pixels in the scene are examined to determine whether or not they lie within the above limits and if they do they are then included in the classified area.

It was realised at the outset that the test area was too small and the terrain insufficiently rugged for a reliable comparison to be made of different classification techniques. The test area was initially selected because it would not involve too much effort to digitise as its main purpose was to assist in developing the algorithms for utilizing terrain data. Problems were also encountered in trying to establish ground truth to verify the classifications. It was decided to try to classify areas of woodland since reliable information as to the extent of woodland in the area was available from the Forestry Commission. Most of the remainder of the test area was farmland. An outline was therefore drawn around the main areas of woodland but approximately 50 m inside the boundary to remove uncertainties that might arise from a possible misregistration between the Landsat image and the map data. (This is discussed in more detail later.) Using the outlines drawn, the Landsat pixels that were associated with woodland were determined. A further difficulty arose because the woodland was largely a mixture of coniferous and deciduous trees and this mixture was different for different areas. Also, as the Landsat data was obtained in late Autumn the different species of deciduous trees were at different stages of shedding their foilage. Because of all these difficulties it was realised that little faith could be put in any conclusions drawn from the results obtained but nevertheless the exercise in itself was considered to be useful.

It was decided to compare the classifications obtained when using the following three types of data:

(1) The original Landsat data.

(2) The original Landsat data after ratioing. (In this case each band is divided by the sum of all four bands, the rationale for this being that the resultant four image planes should be independent of the level of illumination. This method was chosen for examination because it is the one commonly employed for attempting to remove the topographic effect.)

(3) The illumination corrected Landsat data.

The results of the classification are given in Table 2. The second column represents the total number of pixels in the subscene that are classified as being mixed woodland whereas the third column represents the number of classified pixels coincident with pixels that were definitely known to be associated with mixed woodland. The last column represents the proportion of the test areas of mixed woodland correctly classified. The two important points to note are that the classifications with the original data and the illumination corrected data are equally successful and that the ratio method produced much poorer results. It is often found that the ratio method gives inferior results compared with classifications using the original data because although in principle it removes the effect of different levels of illumination it is at the expense of losing intensity information which might be essential for a successful classification.

A comparison was also made between the intensity distributions of the pixels covering the woodland areas, both before and after the topographic correction was applied. What one would expect to find if the correction improves the data for classification is that the variance of the pixel intensities is smaller after the correction is applied. The results obtained can be seen in Table 3. These show that after the correction the variance is smaller for band 7, unchanged for band 6, greater for band 5 and greater still for band 4. The reasons for this are not clear. One possible explanation is that the assumption concerning the relative contribution of the diffuse skylight is incorrect. The assumption made was that for each band it represented 12% of the total illumination on flat terrain. However, it would be expected that the relative contribution would be greater at the shorter wavelengths because the effect of scattering by dust particles and water droplets in the atmosphere is greater at these wavelengths. Also, no account has been taken of the fact that the diffuse contribution is anisotropic, this being manifest as an increase in intensity near the horizon and in the circumsolar region of the sky. Another possibility is that account needs to be taken of the scattering properties of the type of woodland under consideration, data which at present is not available to the author.

6.3 Discussion

Having developed the relevant techniques for using terrain data with Landsat imagery the next step is to carry out a comprehensive analysis of improvements in the accuracy of classification arising from knowledge of the terrain. When selecting a new test area for this analysis four criteria will need to be satisfied:

(1) The area should be much larger than the test area used here.

(2) The terrain should be considerably more rugged than for the test area used here.

(3) Very accurate ground truth information should be available to verify classifications.

(4) Very good terrain data is required, *eg* height contours every 25 ft. It would also be interesting to determine how any improvement in classification changed as the quality of the map data used to generate the height matrix was reduced.

At present, the most promising method for employing terrain data to improve classification accuracy is for the variation in direct illumination to be used as an extra image plane. Trying to correct an image so that it appears as it would were the terrain flat rather than undulating has the disadvantage that both the contribution of the diffuse skylight and the scattering properties of the cover type of interest need to be known, two quantities that are rather awkward to determine.

One problem that has been ignored so far is that arising from possible misregistration between the Landsat data and the map data resulting in a height (or other terrain parameter) estimate associated with a particular pixel not being associated with that pixel but with a nearby pixel instead. The misregistration arises from the positional uncertainty in both the Landsat data and the map data. The accuracy of the Landsat data after geometrical correction is typically about 50 m, this value representing the root mean square value of the differences between the positions of ground control points on the map and on the Landsat image. For an Ordnance Survey map, the vertical accuracy of the contours can be taken as being approximately equivalent to a quarter contour interval, however Ref 7 should be consulted for a precise definition of contour accuracy. Thus, the misregistration is likely to be greatest for flat and undulating terrain where contours are widely spaced, and smallest for very rugged terrain where the contours are very closely spaced. Conversely, the problem of misregistration is most serious when the slope of the terrain is changing rapidly compared with the pixel size of the Landsat data. In these areas the method cannot be expected to improve the accuracy of classifications and indeed may even degrade them.

7 CONCLUSIONS

A technique has been described that can be used to generate a terrain height matrix from a set of height contours. The use of this terrain matrix to derive slope, aspect, and the variation in direct solar illumination has also been described. As an example these parameters were derived from data obtained from an Ordnance Survey map and presented in the form of grey tone images. Finally, the terrain data was used to demonstrate how an attempt could be made to reduce the topographic effect on Landsat imagery. It was concluded that in order to establish any improvement in classification accuracy arising from the use of terrain data with Landsat imagery, a large test area is needed for which accurate ground truth data is available. It is expected that attempts to use terrain data with Landsat and other imagery of land surfaces will increase as both the availability and quality of suitable topographic data bases improves and provision is made for its routine use.

Table 1

HEIGHT MATRIX COMPARED WITH SPOT HEIGHTS FOR FIG 1

Spot height (ft)	Grid height (ft)	Difference (ft)
436.0	433.7	2.3
343.0	346.4	-3.4
365.0	359.3	5.7
313.0	320.6	-7.6
353.0	358.2	-5.2
281.0	294.2	-13.2
335.0	330.7	4.3
318.0	321.8	-3.8
602.0	600.9	1.1
394.0	400.4	-6.4
379.0	378.1	0.9
367.0	366.4	0.6
442.0	428.6	13.4
489.0	481.7	7.3
414.0	419.6	-5.6
453.0	436.4	16.6
381.0	381.8	-0.8
316.0	320.9	-4.9
377.0	376.5	0.5
571.0	566.9	4.1
329.0	335.7	-6.7

Mean difference: -0.04 ft

Standard deviation of the difference: 7.1 ft

Table 2

COMPARISON OF CLASSIFICATIONS

Data used	Total number of pixels classified	Number of pixels classified within the test areas*	Percentage of test areas classified
Original	1000	446	52
Original ratioed	1115	336	39
Illumination corrected	967	432	50

* Test areas cover 866 pixels.

Table 3

PIXEL STATISTICS FOR WOODLAND AREAS BEFORE AND AFTER ILLUMINATION CORRECTION

Band	Wavelength range (μm)	Mean pixel intensity Variance of pixel intensities	
		Before correction	After correction
4	0.5 to 0.6	80 17	79 137
5	0.6 to 0.7	55 24	54 60
6	0.7 to 0.8	90 109	88 105
7	0.8 to 1.1	102 245	99 151

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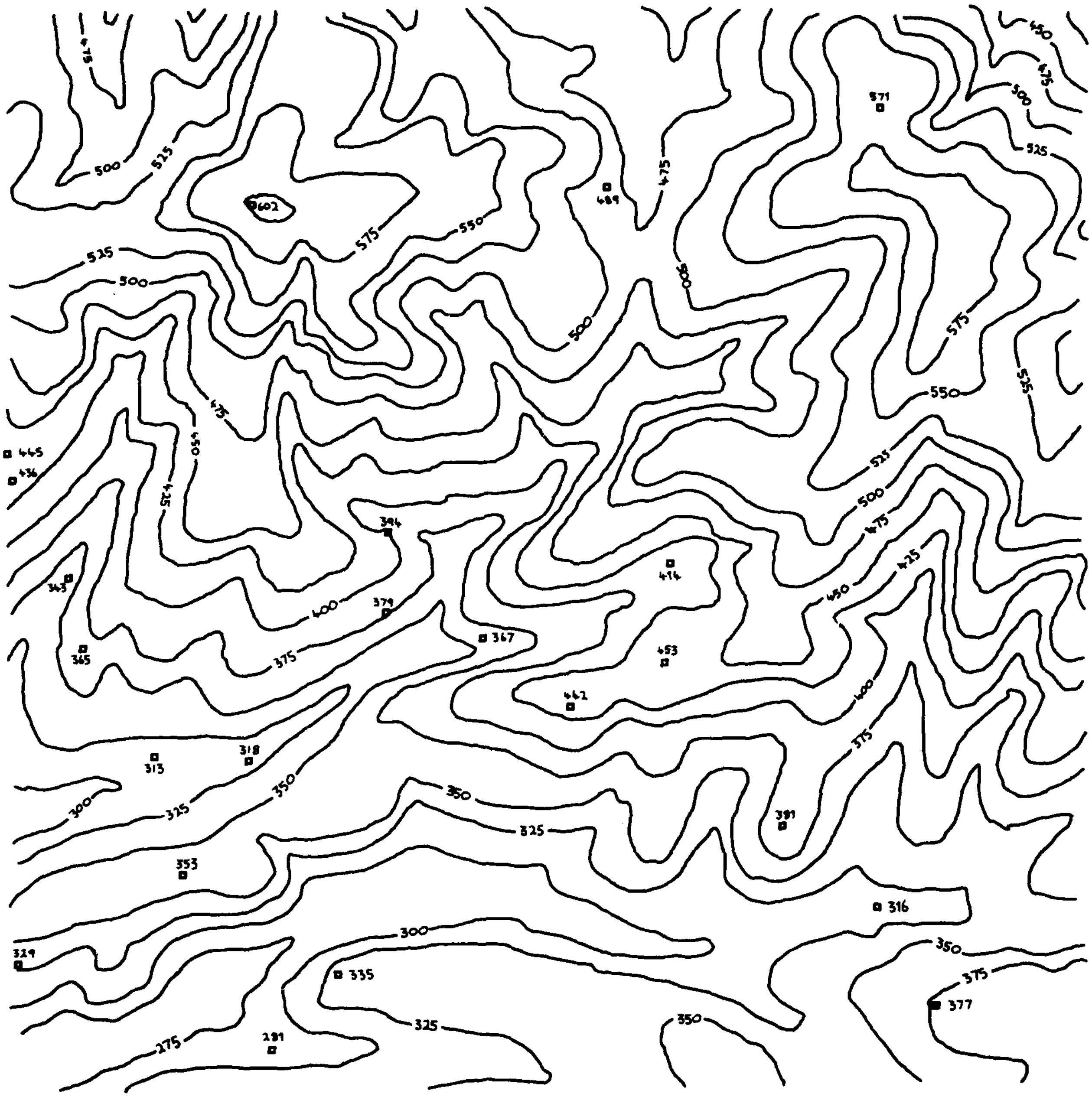

Fig 1 A 5 km square of Ordnance Survey map SU54 after digitisation of contours and spot heights

(Note: all heights are in feet)

Fig 2a-d

(a) Height

(b) Slope

N

(c) Aspect

(d) Variation in direct solar illumination

(The sun is at an elevation of 15° and an azimuth of 159° from North)

Fig 2 Grey tone image representation of the four terrain parameters for the central 4 km square of the test area The pixel size is 50 m

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(a) Before correction

(b) After correction

Fig 3 Landsat band 7 for the central 4 km square of the test area before and after correcting for the topographic effect. The pixel size is 50 m

REPORT DOCUMENTATION PAGE

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1. DRIC Reference (to be added by DRIC)	2. Originator's Reference	3. Agency Reference	4. Report Security Classification/Marking
	RAE TM Space 297	N/A	UNCLASSIFIED

5. DRIC Code for Originator	6. Originator (Corporate Author) Name and Location
7673000W	Royal Aircraft Establishment, Farnborough, Hants, UK
5a. Sponsoring Agency's Code	**6a. Sponsoring Agency (Contract Authority) Name and Location**
N/A	N/A

7. Title The Use of Terrain Height Information for Improving the Accuracy of Classification of Landsat data

7a. (For Translations) Title in Foreign Language

7b. (For Conference Papers) Title, Place and Date of Conference

8. Author 1. Surname, Initials	9a. Author 2	9b. Authors 3, 4	10. Date	Pages	Refs.
Roberts, P.A.			January 1982	17	7

11. Contract Number	12. Period	13. Project	14. Other Reference Nos.
N/A	N/A		

15. Distribution statement
(a) Controlled by – Head of Space Department, RAE
(b) Special limitations (if any) –

16. Descriptors (Keywords) (Descriptors marked * are selected from TEST)

Remote sensing. Terrain analysis. Landsat. Classification.

17. Abstract

One potentially important area of work in remote sensing is the use of topographic data in conjunction with satellite imagery to improve the accuracy of classification algorithms. This Memorandum is concerned with techniques for using terrain height data in conjunction with Landsat imagery. An algorithm is described that transforms digitised height contours into an equispaced grid of points. A method is also described which utilises this height matrix to derive the magnitude and direction of the slope of the terrain, information which can in turn be used to calculate the variation in direct solar illumination over an area. Finally, techniques are described for using terrain data to improve the accuracy of multispectral classification of Landsat data.

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